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WHALE OPTIMIZED PID CONTROLLERS FOR LFC OF TWO AREA INTERCONNECTED THERMAL POWER PLANTS

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Abstract

This paper elaborates the application of new nature inspired algorithm; 'Whale Optimization Algorithm (WOA)' in load frequency control of two area interconnected non-reheat thermal power plants. Two number of PID controllers have been considered in the investigated system and the parameters of the controllers have been tuned/optimized using WOA. The design problem has been formulated as the constrained optimization problem with upper and lower bounds of controller's parameters. The integral of time multiplied absolute error (ITAE) has been taken as an objective function in the present work. The parameters of controllers (K_P, K_I, K_D), minimum damping ratio (MDR), the values of performance indices (ITAE, ISTE, ISE, IAE), settling times and overshoots of Δf_1, Δf_2 and ΔP_{Tie} have also been evaluated for the system under investigation using WOA. The simulation results include the dynamic responses of Δf_1, Δf_2 and ΔP_{Tie} for different step load changes from 0.1p.u. to 0.5p.u in area 1 by keeping constant 0.1p.u. step load change in area 2. It has been observed that smooth and better dynamic responses with fewer oscillations, less settling times and less overshoots can be achieved for the system using WOA.

Keywords:

Load Frequency Control (LFC), Two Area Interconnected Non Reheat Power System, PID Controllers, Whale Optimization Algorithm (WOA)

1. INTRODUCTION

The intelligent system has now been a necessary part to manage and control the large power systems with knowledge, techniques and methodologies for the real-time control of power systems [1]. The multi area power systems involve an important control process, named as 'Automatic Generation Control (AGC)' to:

- Make a balance between generation and load at a minimum cost.
- Monitor as well as control the system frequency, power interchange and tie-line flows.
- Keep the time average of frequency deviations and tie-line power deviations at a low value [2]-[4].

Over the years Load Frequency Control (LFC) has been a necessary part of Automatic Generation Control (AGC) in electric power system and it is used to control the load frequency for making operation of the power system safe [2]-[4]. Various controllers for the LFC problems such as; I, PI, PID, IDD, FOPID and PIDD have already been implemented and compared in literatures [5]-[10] and it has been shown that the conventional PID controllers are most widely applicable frequency controller among all reported controllers [11].

Researchers are continuously contributing their research work in the field of soft computing based optimization methods for LFC/AGC of multi area power system such as; adaptive Fuzzy gain scheduler for LFC/AGC [12], PID controllers optimized by BFOA [13], craziness based PSO optimized controllers in a thermal power system [14]. ICA tuned PID controllers in multi area power system [15], DE tuned classical controllers for MAMS-PS [16], TLBO to design I/PID controllers for MUMS-PS [17], an intelligent controller based on emotional learning for LFC system [18], FA with on line wavelet filter for interconnected unequal three area power system [22], ABC for AGC system [19], ABC algorithm in AGC of interconnected reheat thermal power system [20], GSA to optimize the parameters of PI/PIDF controller for AGC system [21], a hybrid BFOA-PSO algorithm for AGC systems [22], hPSO-PS algorithm for optimization of the fuzzy PI controller parameters [23], DE optimized 2DOF-PID controllers for LFC system [24], hGWO-PS based 2DOF-PID controllers for multi area interconnected power systems [25], [26], [28] have already been available in the literature. A detailed performance comparison of multi area power systems using Ant Colony Optimization technique with different objective functions has been given in [30].

In present work, a novel nature-inspired meta-heuristic optimization algorithm, named; Whale Optimization Algorithm (WOA) [27] has been applied to LFC/AGC of two area interconnected non reheat thermal power plant. WOA is based on the social behavior of humpback whales [29]. The inspiration of algorithm is obtained by the bubble-net hunting strategy. This algorithm is very competitive as compared to the state-of-art meta-heuristic algorithms as well as conventional methods [27]. As PID controllers have become most widely used frequency controllers due to its simplicity [11], these controllers have also been used for the system aforementioned and WOA has been used to optimize the parameters of PID controllers using ITAE as an objective function.

In section 2, two area power system of thermal power plants have been described. The brief explanation of PID controller has been given in section 3. In section 4, the constrained optimization problem with integral of time multiplied absolute error (ITAE) as an objective function, upper and lower parameter bounds of the work have been defined. The overview of whale optimization algorithm has been elaborated in section 5. In section 6, application of WOA to the aforementioned system has been described. Section 7 deals with simulation results. In section 8, conclusions of the present work have been summarized followed by the references at the end.

2. BASIC CONCEPTS

In present work, the widely used two areas interconnected non reheat thermal power system [21]-[27] has been considered for the sake of analysis, as shown in Fig.1. The design parameters for the system have been described as [21]-[26]:

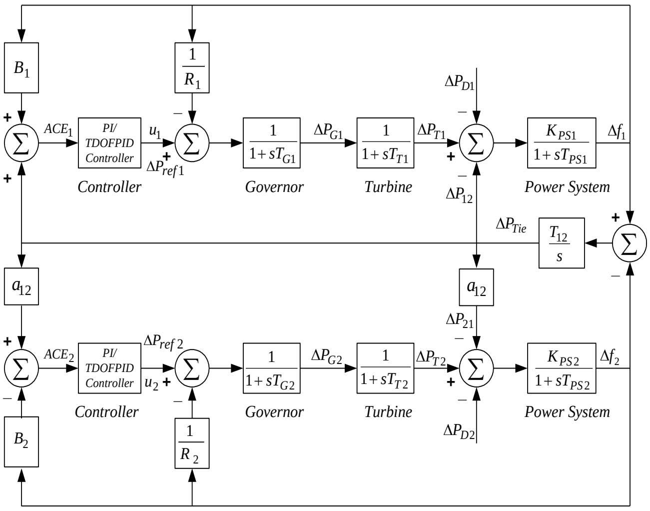

Fig.1. Block diagram of two area thermal power plant

P_R = 2000MW (rating), P_L = 1000MW (nominal loading); f =60Hz, B_1, B_2 = 0.425p.u. MW/Hz; $R_1 = R_2$= 2.4Hz/p.u.; $T_{G1} = T_{G2}$ = 0.08s; $T_{T1} = T_{T2}$ =0.3s; $K_{PS1}= K_{PS2}$ =120Hz/p.u. MW; $T_{PS1} = T_{PS2}$ = 20s; T_{12} = 0.545pu. Each block in Fig.1 represents the transfer function of respective plant. The mathematical analysis of the same can be found in [25]-[26].

3. PROPORTIONAL INTEGRAL DERIVATIVE (PID) CONTROLLERS

In present work, two Proportional Integral Derivative (PID) controllers with similar characteristics have been considered in both areas of the system under investigation. Three parameters are used to represent the PID controller and these are known as Proportional Gain (K_P), Integral Gain (K_I) and Derivative Gain (K_D). Hence, the parameters of PID controllers are defined as follows:

$$K_{P1} = K_{P2};\ K_{I1} = K_{I2};\ K_{D1} = K_{D2} \tag{1}$$

The Area Control Errors ACE_1 and ACE_2 are basically the errors; $e_1(t)$ and $e_2(t)$ to the PID controllers in area 1 and area 2, respectively. The control inputs to the controllers are defined as:

$$u_1(t) = K_{P1}e_1(t) + K_{P1}\int e_1(t)dt + K_{D1}\frac{de_1(t)}{dt} \tag{2}$$

$$u_2(t) = K_{P2}e_2(t) + K_{P2}\int e_2(t)dt + K_{D2}\frac{de_2(t)}{dt} \tag{3}$$

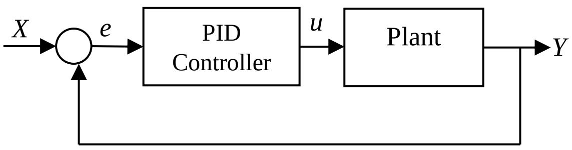

Fig.2. Closed loop control system with PID controller

where,

$$e_1(t) = ACE_1 \text{ and } e_1(t) = ACE_1$$

so,

$$u_1(t) = K_{P1}ACE_1(t) + K_{I1}\int ACE_1(t)dt + K_{D1}\frac{dACE_1(t)}{dt} \tag{4}$$

$$u_2(t) = K_{P2}ACE_2(t) + K_{I1}\int ACE_2(t)dt + K_{D2}\frac{dACE_2(t)}{dt} \tag{5}$$

4. OPTIMIZATION PROBLEM WITH OBJECTIVE FUNCTION, UPPER AND LOWER BOUND CONTROLLER'S PARAMETERS

Integral of time multiplied absolute error (ITAE) is used as an objective function instead of ISE, ISTE and IAE because it exhibits the better dynamic response than others and it is defined as,

$$J_1 = \int_0^{t_s} w_1\left(|\Delta f_1| + |\Delta f_2| + |\Delta P_{tlf}|\right)tdt \tag{6}$$

where, Δf_1, Δf_2 represent system frequency deviations; ΔP_{Tie} is incremental change in tie-line power and t_s denotes time range of simulation.

The controller parameter's bounds are the problem constraints. Therefore, the design problem can be formulated as following optimization problem:

Subject to,

$$\begin{aligned} K_{Pmin} \le K_P \le K_{Pmax}, \\ K_{Imin} \le K_I \le K_{Imax}, \\ K_{Dmin} \le K_D \le K_{Dmax} \end{aligned} \tag{7}$$

The parameters in Eq.(7) are tabulated in Table.1.

Table.1. Parameters values and range

Parameters	Description	Value
K_{Pmin}, K_{Pmax}	Minimum and maximum value of proportional gain	[-2, 2]
K_{Imin}, K_{Imax}	Minimum and maximum value of integral gain	[-2, 2]
K_{Dmin}, K_{Dmax}	Minimum and maximum value of derivative gain	[-2, 2]

5. WHALE OPTIMIZATION ALGORITHM (WOA)

WOA algorithm starts with a set of random solutions. Search agents update their positions at each iteration with respect to either a randomly chosen search agent or the best solution obtained so far. For initiating the exploration and exploitation, parameter a is decreased from 2 to 0, respectively. $|\bar{A}| > 1$ leads to a random search agent while $|\bar{A}| < 1$ leads to the best solution for updating the position of the search agents. WOA can switch between either spiral or circular movement depending on the value of p. After being satisfied by the termination criteria, finally, the WOA algorithm terminates. WOA can be considered as a global optimization algorithm since it involves exploration and exploitation ability. Furthermore, a search space is provided in the neighborhood of the best solution which allows other search agents to exploit the current best record inside that domain. The adaptive variation is found in the search Vector *A* tending to allow the WOA algorithm to smoothly transit between exploration and exploitation.

- $|A| \geq 1$ leads to some iteration devoted to exploration.
- $|A| < 1$ leads to rest of the iteration devoted to exploitation.

Although mutation and other evolutionary operations might have been included in the WOA formulation to fully reproduce the behavior of humpback whales, the amount of heuristics and the number of internal parameters are decided to be minimized, thus implementing a very basic version of the WOA algorithm. The pseudo code of the WOA algorithm is as under [27]:

Table.2. Pseudocode of WOA [27]

```
Initialize the whales population Xi(i = 1,2,...,n)
Calculate the fitness of each search agent
X*= the best search agent
While (t < maximum number of iterations)
    For each search agent
        Update a, A, C, l, and p
        If 1 (p < 0.5)
            If 2 (|A| < 1)
                Update the position of the current search agent
            Else if 2 (|A| ≥ 1)
            Select a random search agent (Xrand)
            Update the position of the current search agent
            End if 2
        Else if 1 (p ≥ 0.5)
        Update the position of the current search
        End if 1
    End for
    Check if any search agent goes beyond the search space
and amend it
    Calculate the fitness of each search agent
    Update X* if there is a better solution
    t = t+1
    End while
Return X*
```

The detailed mathematical modeling of WOA can be found in Mirjalili et al. 2016 [27].

6. APPLICATION OF WOA IN SYSTEM UNDER CONSIDERATION

Whale optimization algorithm has been employed to two area thermal power system in order to enhance the performance of the whole plant. Matlab/Simulink software has been used to implement the model of the aforementioned system and pseudo codes of the algorithm. Two number of PID controllers with similar characteristics have been considered in each area of thermal system for load frequency control. A 10% step load change in area-1 is considered in order to simulate the model. Series of runs are executed to select the algorithm parameters properly. Number of search agents and iterations are taken as 20 and 50, respectively. The optimization was repeated 10 times and the best final solution among the 10 runs is chosen as controller's parameters. The best set of values corresponding to the minimum objective function provided by optimal WOA have been chosen the final optimal parameters of the controllers, as listed in Table.3.

Table.3. WOA optimized parameters of PID controllers

Controllers' Parameters	Optimization method	Value
K_P	WOA	1.1376
K_I	WOA	1.9960
K_D	WOA	0.3982

The convergence of objective function, i.e. ITAE with number of iterations for obtaining the above parameters of two PID controllers in each area is shown in Fig.3 and obtained value of ITAE is 0.1312.

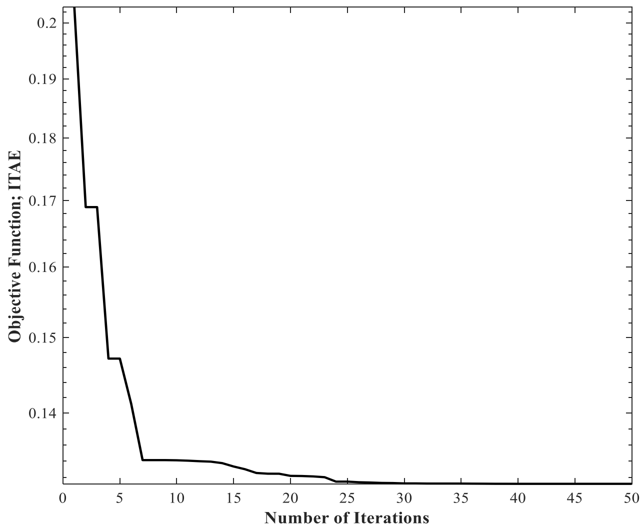

Fig.3. Convergence of objective function, ITAE with number of iterations

7. SIMULATION RESULTS AND DISCUSSIONS

The simulation has been performed for PID controllers optimized by WOA and results have been elaborated on the basis of system's dynamic response, settling times and overshoots of Δf_1, Δf_2 and ΔP_{Tie}. The simulation results show that the WOA optimized PID controllers for the aforementioned system provides better results in terms of performance indices (ITAE, ISE, ITSE, IAE), system dynamic response, settling times and overshoots Δf_1, Δf_2 and ΔP_{Tie}.

7.1 PERFORMANCE INDICES AND MDR

At t = 0 second, a 10% step load increase in area-1 is considered and the values of ITAE, ISTE, IAE and ISE for PID controllers optimized by WOA are given in Table.4. It can be seen in Table 4 that, less values of performance indices can be obtained for the system using WOA, i.e. enhanced performance of the power plant. Also, the obtained value of minimum damping ratio (MDR) is 0.0786.

Table.4. Values of performance indices and MDR

Performance Indices	Value
ITAE	0.1312
ISE	0.0080
ITSE	0.0044
IAE	0.1520
MDR	0.0786

7.2 SYSTEM DYNAMIC RESPONSE

The study of the time domain simulations have been elaborated for 10% step load change in area 1 at time t = 0 second. The dynamic responses of WOA optimized PID controllers for the system under study are shown in Fig.4 - Fig.6. The simulation results show that the significant improvement in the dynamic responses (Fig.4-Fig.6) can be obtained by WOA.

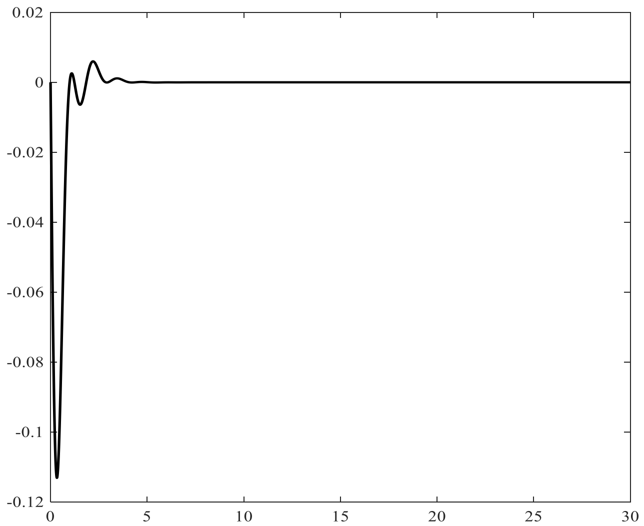

Fig.4. Frequency deviation at area 1; Δf_1 (Hz)

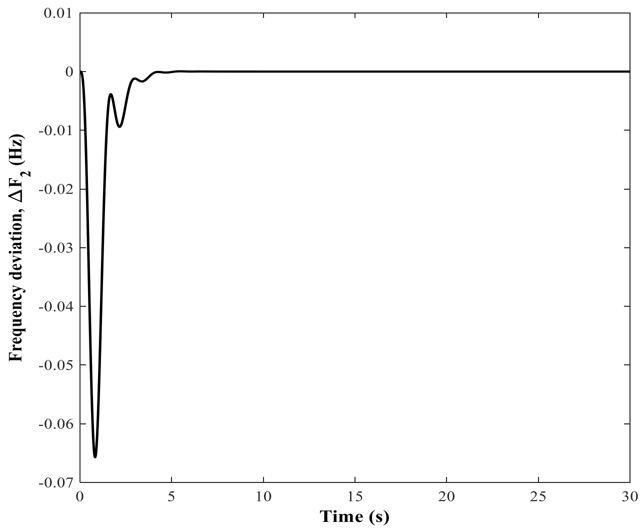

Fig.5. Frequency deviation at area 2; Δf_2 (Hz)

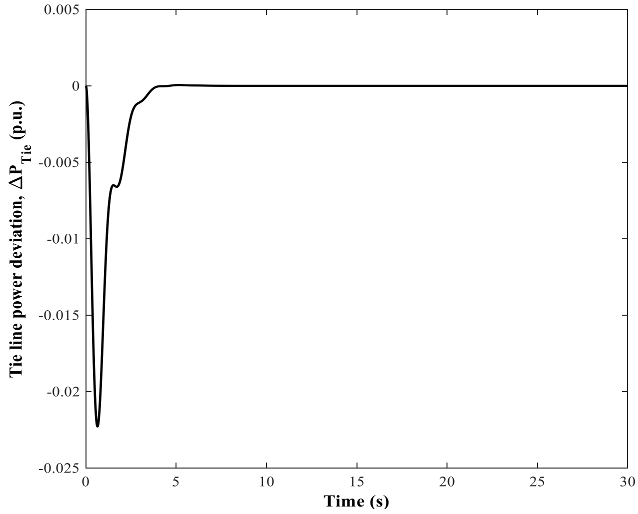

Fig.6. Tie line power deviation; ΔP_{Tie} (p.u.)

7.3 SETTLING TIMES AND OVERSHOOTS

For better illustration of WOA optimized PID controllers for LFC, the settling times in frequency and tie-line power deviations have also been evaluated and summarized in Table.4, which shows that far better system performance in terms of settling times and overshoots can be obtained with WOA optimized PID controllers for the system under investigation.

Table.4. Settling times and overshoots

<table>
<tr><th rowspan="2">Approach</th><th rowspan="2">ITAE value</th><th colspan="3">Settling times (2% band) T_s (sec)</th></tr>
<tr><th>Δf_1</th><th>Δf_2</th><th>ΔP_{tie}</th></tr>
<tr><td rowspan="4">WOA optimized PID controller</td><td rowspan="4">0.1312</td><td>2.63</td><td>2.81</td><td>2.55</td></tr>
<tr><td colspan="3">Overshoot</td></tr>
<tr><td>Δf_1</td><td>Δf_2</td><td>ΔP_{tie}</td></tr>
<tr><td>0.005989</td><td>0.000044</td><td>0.00005371</td></tr>
</table>

7.4 DYNAMIC RESPONSES WITH LOAD VARIATION

In this section, the step load is varied from 10% to 50% in area 1 by keeping constant 10% step load change in area 2 and the dynamic behavior of the system corresponding to load change are shown in Fig.7, Fig.8 and Fig.9. At each load disturbance, good dynamic response is obtained with approximately same settling times for the same parameters of PID controllers, as given in Table.3. Therefore, WOA optimized PID controllers' makes the system more robust.

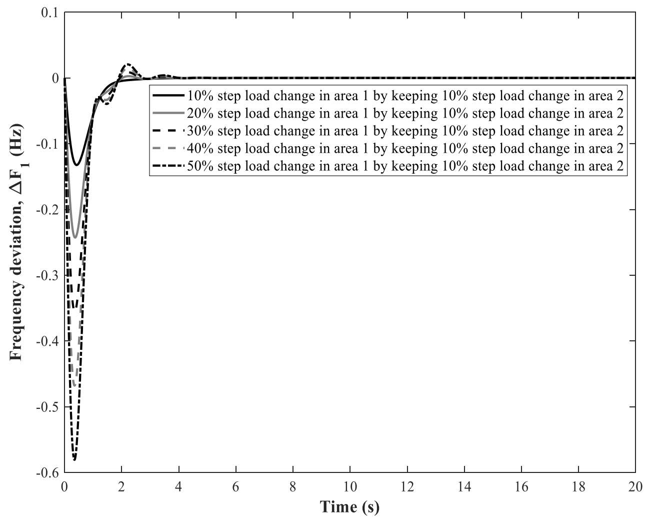

Fig.7. Frequency deviation at area 1; Δf_1 (Hz) with variations in load

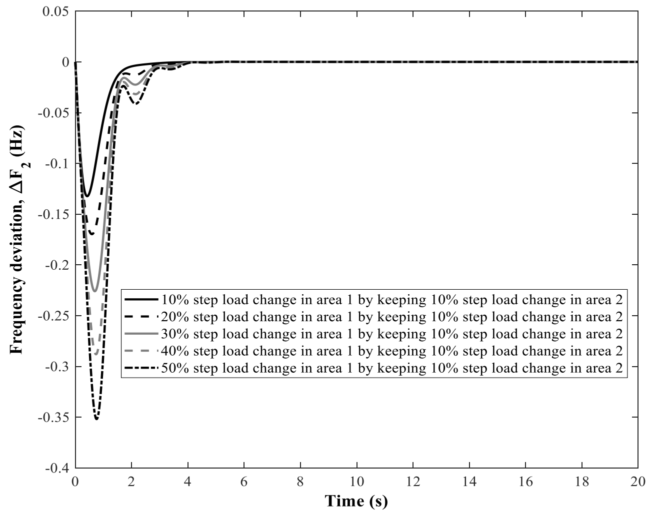

Fig.8. Frequency deviation at area 2; Δf_2 (Hz) with variations in load

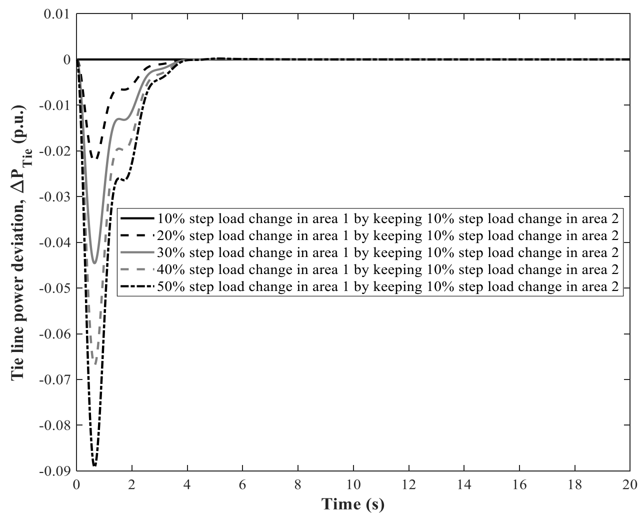

Fig.9. Tie line power deviation; ΔP_{Tie} (p.u.) with variations in load

8. CONCLUSIONS

A new natured inspired algorithm named; Whale optimization (WOA) has been employed in order to optimize the parameters of PID controllers in two areas interconnected non reheat thermal power system for the purpose of load frequency control and to enhance the performance of the system. The ITAE as an objective function has been taken for the constrained optimization problem with upper and lower controller's parameters bounds. Matlab or Simulink environment has been used to implement the model of the system under investigation and the pseudo codes of the WOA algorithm. The performance indices; ITAE, ISTE, ISE, IAE and minimum damping ratio (MDR) have also been evaluated. The simulation results reveal that the system with PID controllers optimized by WOA exhibits the outstanding results in terms of less values of performance indices, better dynamic responses, less settling times and less overshoots of Δf_1, Δf_2 and ΔP_{Tie}. It has also been observed that the system with WOA optimized PID controllers becomes more robust to variations in load with less oscillations.

REFERENCES

[1] R.C. Bansal, "Optimization Methods for Electric Power Systems: An Overview", *International Journal of Emerging Electric Power Systems*, Vol. 2, No. 1, pp. 1-6, 2005.

[2] P. Kundur. "*Power System Stability and Control*", Tata McGraw Hill, 2009.

[3] O.I. Elgerd, "Electric Energy Systems Theory-An Introduction", Tata McGraw Hill, 2000.

[4] D.P. Kothari and I.J. Nagrath, "*Power System Engineering*", 2nd Edition, Tata McGraw Hill, 2010.

[5] P. Bhatt, S.P. Ghoshal and R. Roy, "Load Frequency Stabilization by Coordinated Control of Thermistor Controlled Phase Shifters and Superconducting Magnetic Energy Storage for Three Types of Interconnected Two-Area Power Systems", *International Journal of Electrical Power and Energy Systems*, Vol. 32, pp. 1111-1124, 2012.

[6] U.K. Rout, R.K. Sahu and S. Panda, "Design and Analysis of Differential Evolution Algorithm based Automatic Generation Control for Interconnected Power System", *Ain Shams Engineering Journal*, Vol. 4, No. 3, pp. 409-421, 2013.

[7] S. Panda and N.K. Yegireddy, "Automatic Generation Control of Multi-Area Power System using Multi-Objective Non-Dominated Sorting Genetic Algorithm-II", *International Journal of Electrical Power and Energy Systems*, Vol. 53, pp. 54-64, 2013.

[8] L.C. Saikia, J. Nanda and S. Mishra, "Performance Comparison of Several Classical Controllers in AGC for Multi-Area Interconnected Thermal System", *International Journal of Electrical Power and Energy Systems*, Vol. 33, pp. 394-401, 2013.

[9] S.A. Taher, M.H. Fini and S.F. Aliabadi, "Fractional Order PID Controller Design for LFC in Electric Power Systems using Imperialist Competitive Algorithm", *Ain Shams Engineering Journal*, Vol. 5, No. 1, pp. 121-135, 2014.

[10] S. Debbarma, L.C. Saikia and N. Sinha, "Robust Two-Degree-of-Freedom Controller for Automatic Generation Control of Multi-Area System", *International Journal of*

Electrical Power and Energy Systems, Vol. 63, pp. 878-886, 2014.

[11] L.C. Saikia, J. Nanda and S. Mishra, "Performance Comparison of Several Classical Controllers in AGC for Multi-Area Interconnected Thermal System", *International Journal of Electrical Power and Energy Systems*, Vol. 33, pp. 394-401, 2011.

[12] J. Talaq and F. Al-Basri, "Adaptive Fuzzy gain scheduling for Load Frequency Control", *IEEE Transaction on Power System*, Vol. 14, No.1, pp. 145-150, 1999.

[13] E.S. Ali and S.M. Abd-Elazim, "Bacteria Foraging Optimization Algorithm based Load Frequency Controller for Interconnected Power System", *International Journal of Electrical Power and Energy Systems*, Vol. 33, pp. 633-638, 2011.

[14] H. Gozde and M.C. Taplamacioglu, "Automatic Generation Control Application with Craziness based Particle Swarm Optimization in a Thermal Power System", *International Journal of Electrical Power and Energy Systems*, Vol. 33, pp. 8-16, 2011.

[15] H. Shabani, B. Vahidi and M. Ebrahimpour, "A Robust PID Controller based on Imperialist Competitive Algorithm for Load-Frequency Control of Power Systems", *ISA Transactions*, Vol. 52, No. 1, pp. 88-95, 2012.

[16] B. Mohanty, S. Panda and P.K. Hota, "Controller Parameters Tuning of Differential Evolution Algorithm and its Application to Load Frequency control of Multi-Source Power System", *International Journal of Electrical Power and Energy Systems*, Vol. 54, pp. 77-85, 2014.

[17] A.K. Barisal, "Comparative Performance Analysis of Teaching Learning based Optimization for Automatic Load Frequency Control of Multi-Sources Power Systems", *International Journal of Electrical Power and Energy Systems*, Vol. 66, pp. 67-77, 2015.

[18] Ehsan Bijami, Rohollah Abshari, Seyed Morteza Saghaiannejad and Javad Askari, "Load Frequency Control of Inter- Connected Power System using Emotional Learning based Intelligent Controller", *Proceedings of 19th Iranian Conference on Electrical Engineering*, pp. 76-83, 2012.

[19] K. Naidu, H. Mokhlis, A.H.A. Bakar, V. Terzija and H.A. Illias, "Application of Firefly Algorithm with Online Wavelet Filter in Automatic Generation Control of an Interconnected Reheat Thermal Power System", *International Journal of Electrical Power and Energy Systems*, Vol. 63, pp. 401-413, 2014.

[20] H. Gozde, M.C. Taplamacioglu and I. Kocaarslan, "Comparative Performance Analysis of Artificial Bee Colony Algorithm in Automatic Generation Control for Interconnected Reheat Thermal Power System", *International Journal of Electrical Power and Energy Systems*, Vol. 42, pp. 167-178, 2012.

[21] R.K. Sahu, S. Panda and S. Padhan, "Optimal Gravitational Search Algorithm for Interconnected Power Systems", *Ain Shams Engineering Journal*, Vol. 5, No. 3, pp. 721-733, 2014.

[22] S. Panda, B. Mohanty and P.K. Hota, "Hybrid BFOA-PSO Algorithm for Automatic Generation Control of Linear and Nonlinear Interconnected Power Systems", *Applied Soft Computing*, Vol. 13, No. 12, pp. 4718-4730, 2013.

[23] R.K. Sahu, S. Panda and G.T.C. Sekher, "A Novel Hybrid PSO-PS Optimized Fuzzy PI Controller for AGC in Multi-Area Interconnected Power System", *International Journal of Electrical Power and Energy Systems*, Vol. 64, pp. 880-893, 2015

[24] R.K. Sahu, S. Panda and U.K. Rout, "DE Optimized Parallel 2-DOF PID Controller for Load Frequency Control of Power System with Governor Dead-Band Nonlinearity", *International Journal of Electrical Power and Energy Systems*, Vol. 49, pp.19-33, 2013.

[25] V. Soni, G. Parmar, M. Kumar and S. Panda, "HGWO-PS Optimized 2DOF-PID Controller for Non Reheat Two Areas Interconnected Thermal Power Plants: A Comparative Study", *Proceedings of IEEE Conference on Power Electronics, Intelligent Control and Energy Systems*, pp. 23-28, 2016.

[26] V. Soni, G. Parmar, M. Kumar and S. Panda, "Hybrid Grey Wolf Optimization-Pattern Search (*h*GWO-PS) Optimized 2DOF-PID Controllers for Load Frequency Control (LFC) in Interconnected Thermal Power Plants", *ICTACT Journal on Soft Computing*, Vol. 6, No. 3, pp. 1244-1256, 2016.

[27] S. Mirjalili and A. Lewis, "The Whale Optimization Algorithm", *Advances in Engineering Software*, Vol. 95, pp. 51-67, 2016.

[28] V. Soni, G. Parmar and M. Kumar, "A Hybrid Grey Wolf Optimization and Pattern search Algorithm for Automatic Generation Control of Multi Area Interconnected Power Systems", *International Journal of Advance Intelligence Paradigm*, Vol. 9, No. 2, pp. 21-26, 2017.

[29] R. Bhatt, G. Parmar and R. Gupta "Application of WOA in Reduced Order Modelling of LTI Systems", Proceedings of 1st International Conference on Recent Innovations in Electrical, Electronics and Communication Systems, pp. 22-27, 2017.

[30] J. Kaliannan, N. Dey, A.S. Ashour and S. Satapathy, "Performance Evaluation of Objective Functions in Automatic Generation Control of Thermal Power System using Ant Colony Optimization Technique Designed Proportional-Integral-Derivative Controller", *Journal of Electrical Engineering*, Vol. 17, No. 2, pp. 1-17, 2017.